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LABORATORY FACILITIES FOR FLOW IN POROUS MEDIA RESEARCH

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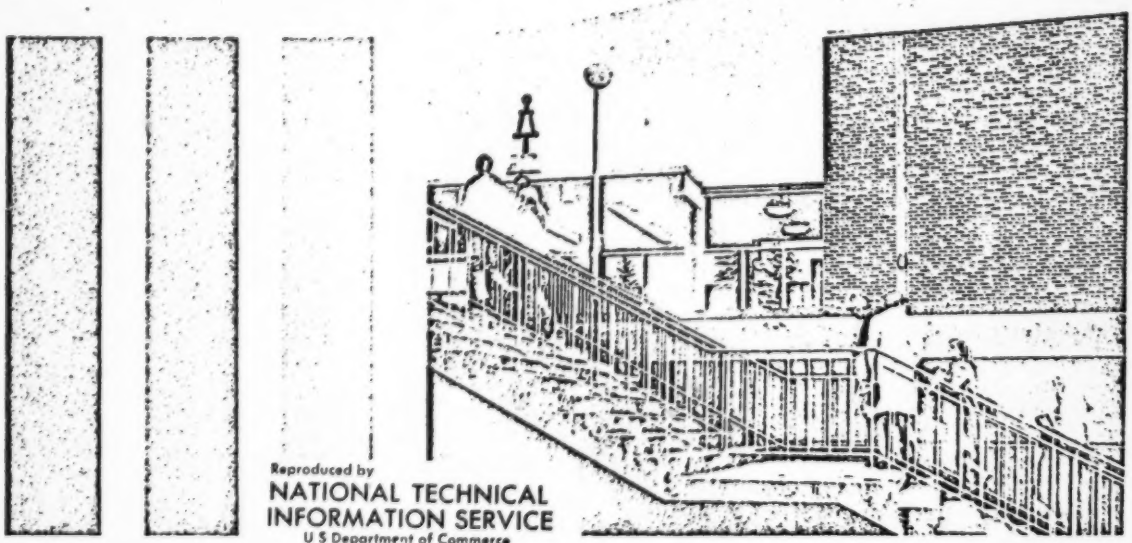

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by

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Presented at the

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ABSTRACT

An enhanced engineering research program at the University of Massachusetts will bring about greater stresses on research facilities with which to study fluid flow through porous media. This paper provides a discussion of a few areas for such research and the facilities which would be utilized in conducting an active research program. The types of research discussed are of particular interest in water resources and environmental engineering.

This discussion of research on flow through porous media is intended to cover several illustrative types of flow problems without any claim to an inclusive coverage of all topics. The topics have been selected on the basis of the writer's previous research experience and his present and future research plans. General requirements for space and equipment are indicated for the different research areas.

A. Evaporation From Soils

Recent studies have shown that more research is needed to overcome the paucity of data which exists regarding the mechanism of evaporation from unsaturated soils (1). There have been reasonably successful attempts to predict from theoretical considerations the amount of evaporation expected from free water surfaces such as lakes. These theoretical models have compared well with actual measurements when sufficient data were available for comparison. The temperature, relative humidity and the turbulent wind structure were the msot important parameters necessary to describe this type of evaporation. A similar type of approach has been used to study evaporation from saturated soils. Results from these studies were subject to greater variance when compared to theoretical predictions than were the results from studies of evaporation from free water surfaces. Experimental studies of evaporation from soils have shown that a number of anomalous results will require a thorough understanding of flow through unsaturated porous mediums before the mechanism of evaporation from these soils is well understood.

In vertical flow of a liquid through a soil gravity forces are normally the predominant driving forces. In very slightly saturated soils the

capillary forces predominate and the gravity forces are of little significance. Between these two extremes where both forces play a role are the cases which are normally found in considering evaporation from soils. For a short period during and immediately after an intense rain the soil interstices may be nearly all saturated. Then follows a period when the surface interstices gradually lose water as it percolates to greater depths and some is lost through surface evaporation. Finally, during an indefinite period until the next rain, the upper soil is largely depleted of water except for that held by capillary forces. Hence, in nature there is a very common situation during which evaporation is taking place from unsaturated soils and the water being evaporated is transported by a combination of capillary and gravity forces.

Study of evaporation from soils would be facilitated by utilizing soils which could be subjected to controlled radiant heat fluxes. The temperature distribution throughout the column could be closely observed by means of thermistors similar to those used by Anderson, Linville, and Sposito (2) to observe temperature fluctuations in soils. The evaporative loss from the soil would be determined from accurate observations of the water added to the bottom of the columns from Mariotte flasks. By controlling the elevation of the Mariotte flasks the elevation of the water table within the column could be varied to permit evaporation under controlled conditions with various depths to the water table. The amount of water stored in the soil would be measured by means of a gamma ray attenuation device. Thus, from a mass balance of the water phase the evaporation is calculable.

The gamma ray spectrometer permits non destructive measurement of the moisture content at any location in the column without destroying the flow

system. Davidson, Biggar, and Nielsen (3) showed that this method allowed determination of the moisture content to a precision of ± 0.0020 cm^3 H_2O/cm^3 soil. Hence, it is probably superior in accuracy to any other method. When a beam of gamma rays is passed through matter, the attenuation of the beam, or the decrease in intensity of the beam with distance, is related to the initial intensity of the beam by the relation

$$I = I_0 e^{-\mu x}$$

where the terms have the following meaning:

I_0 = intensity of radiation incident to the mass,

I = intensity of radiation transmitted through a thickness x of mass,

μ = a linear attenuation coefficient,

x = thickness of mass through which the transmitted beam passes.

The linear attenuation coefficient is easily obtained by measuring I, I_0, and x, then solving for μ (4).

The above relation is very useful for non destructive testing of the moisture content of unsaturated porous mediums in that the amount of mass through which the gamma ray beam must pass will increase as some of the interstices of the medium fill with water. This will result in more attenuation of the beam as the moisture content increases, and the moisture content can be calculated from the attenuation. Another advantage of the gamma ray attenuation method is that it permits a determination of water vapor content as well as liquid water content. This property of the method holds great promise of being very useful in determining the moisture content of the atmosphere above the porous medium. There will be a different attenuation of the gamma ray beam depending on the moisture content of the atmosphere. Thus,

it is possible to measure the moisture content as a function of elevation from the fully saturated region below the water table up through the partially saturated regions above the water table (actually the zone of complete saturation extends some distance above the water table because of the capillary forces) and, finally, even across the surface of the porous medium into the atmosphere.

B. Infiltration Into Soils

It has been pointed out that infiltration of water into a soil is necessarily a two-fluid flow problem if the soil pores are initially unsaturated (5). For water to move into the interstices of the soil the air must be displaced. In many investigations, such as descriptions of ground water recharge by surface spreading and rainwater infiltration, the effects of the displaced air have been ignored. This is justifiable if the gross effects of air resistance are negligible in comparison to the gross effects of the water resistance. In many experimental investigations this is insured by constructing the experimental equipment so that the displaced air may be readily expelled.

In nature there may be deviations from this condition. A zone of low permeability may underlie the surface so that the displaced air has a high flow resistance. Thus, although the water may be in a zone of high permeability, it has been shown that the infiltration rate would be influenced strongly by the air resistance (4). Compressional forces as well as those resulting from flow resistance have to be considered. A state of equilibrium may eventually be reached when the downward force due to the weight of the infiltrate water, atmospheric pressure and capillary forces is counterbalanced by the upward force due to the compressed entrapped air.

Theoretical analyses predicted and experimental observations confirmed a mechanism by which strong capillary forces hindered instead of helped promote infiltration into soils (4). Infiltration into an initially dry soil overlying an impermeable barrier displaces the air which fills the interstices of the dry soil. Unable to escape downward, the air may escape upward in bubbles travelling through large pores, or, if the pores are small and the capillary forces are large, the air is compressed between the wetting front and the barrier. Under certain calculable conditions the air pressure build-up is sufficient to cause sudden horizontal rupturing of the soil at the wetting front and to lift it along with the infiltrating water, forming a cavity. The air-filled cavity breaks the flow passages and infiltration ceases. Observation with soil columns have shown that when provision was made for the displaced air to escape less than one minute was required for the wetting front to move three inches; when the air was not free to escape and the soil ruptured, two weeks were required for the wetting front to move this distance.

In summary the experimental results show the necessity of considering the effects on infiltration rate of air ahead of the wetting front. With fine-grained mediums which develop large capillary forces breaks may be expected to occur in short columns. The location of the break is not predicted accurately from theory, as the theory made no allowance for air escape and friction; both of which are present in the tests. For grain diameters of greater than 0.03 cm breaks become less likely, especially as the column size is increased. Instead there is a counter-flow of air and water. The pressure build-up in the air obviously has a retarding effect on infiltration. For short columns successive breaks may occur especially if the walls of the tube are dirty, or if there is some

contact between portions of the medium above the break and below the break. For longer columns an equilibrium situation may be reached in which the air pressure is great enough to halt infiltration before the column becomes saturated. Over a long period of time minor effects which are usually neglected, such as diffusion of water vapor and air, probably slowly allow the medium to become wet even if a break has occurred. In some of the short columns three weeks were required for the medium to appear wet ahead of the break.

During infiltration in the field the breaks could be expected to occur as isolated pockets or cavities of air rather than as one continuous break. This undoubtedly would have an effect on the infiltration rate, as no flow would occur through the air cavities.

Additional research on laboratory size columns of porous mediums is necessary to elucidate the fundamental physical flow processes occurring during infiltration. Capillary forces may be large, but of varying magnitude due to the heterogeneous size distribution and packing of soils. Artificial media, such as glass beads, may reduce the heterogeneity of the capillary force distribution. Use of fluids other than water would permit conducting experiments over a wider range of Weber and Reynolds numbers.

C. Dewatering Sludges

The handling, concentration, and disposal of water treatment wastes, or sludge, is a problem which is growing rapidly in magnitude. Various industrial processes, and certain water supply facilities produce vast quantities of sludge, of no economic value, the disposal of which creates a large financial burden on both public and private organizations. Discharge to the sanitary sewer or directly into a watercourse are widely used methods

for disposing of water treatment sludge. Lagoons are less frequently, but nevertheless widely used, particularly where they may be utilized simultaneously as the final disposal area. However, discharge of the solids wastes into watercourses may be approaching its demise due to rapidly evolving, stringent water pollution legislation and regulations. The highly turbid, fine suspensions of water treatment wastes are inimical to the concept of a clear, sparkling, stream. They also add to the non-biodegradable load on a sewage treatment plant, should they be discharged to a sanitary sewer. Lagoon disposal may be looked upon as a temporary expedient, but on filling the lagoons new ones must be constructed, the present ones cleaned, or alternative disposal sites located.

Ultimately, land disposal of the solids is seen as the most feasible choice. This avoids adding to the pollution burden of streams, lakes, and watercourses; but may increase the total land requirements of a treatment plant. The sludge, or slurry, may be withdrawn intermittently from the plant and applied to drying beds on which it will first dewater, then dry. Following this it may be removed and trucked to land disposal sites.

The drying beds may be rotated in their use and are ready for reuse after the solids are removed. Volume reduction of the sludge as it is concentrated through the dewatering and drying cycle is vast. A ton of solids may be contained in 200 tons of water when it is discharged from a water treatment plant. The same ton of solids may contain only 300 lbs of water when it is used for land fill.

The basic processes involved in the dewatering and drying of sludge are filtration, evaporation, and consolidation. The filtration process is

one of fluid flow through porous media. For drying beds, these media are the sludge itself and the supporting layers of graded material - sand, ashes, etc. The fluid flow is actuated by gravitational, capillary, and osmotic forces. The evaporation process concerns vapor diffusion resulting from vapor concentration gradients. These gradients are not dependent on media characteristics alone, but involve also meteorological considerations.

The phenomena involved in dewatering and drying are generally well understood for only certain materials. Examples include the drainage of rigid granular soils and the (thermal) drying of commercial materials such as leather, ceramic clay and cereal grains. The current understanding of these processes as applied to sludge is, however, not of this level. Indeed, little is known, partly because the filtration and evaporation usually occur concurrently. Further, the sludge is a complex pseudo-homogenous, porous, colloidal material. The highly compressible nature of the structural lattice and its low tensile strength results in cracking of the surface and a decrease in permeability with decreasing moisture content.

In essence, the problem of sludge dewatering and drying evolves around the ascertainment of moisture transport rates and moisture gradients within the sludge; within the porous supporting media; and within the air-vapor boundary layer.

Work done in this direction by Coackley (6) in 1962 ended in failure because the elctrical resistance measurements to determine the moisture content in situ created ionic migration in the non-hygroscopic water. Determination of moisture and vapor gradients and transport rates in sludges may be used to formulate the dewatering - drying rate of water treatment sludges in beds under various climatic, operating and design conditions.

D. Laboratory Facilities

Facilities utilized for studying flow through porous media can be quite flexible. Roughly, 250 square feet per project would be an estimate of the floor space required for the experimental portion of the three previously discussed projects. Supporting equipment such as drying ovens, balances, and sinks could be estimated to occupy about 200 square feet per project. Special features which are utilized in the research are close temperature control, humidity control and freedom from vibration. Also, the gamma ray spectrometry system needs to be shielded to preclude accidental radiation exposures to the public.

Analog facilities are frequently utilized to study many flow through porous media problems. The electrical analog may show the response of pumping wells to the ground water table environment of a river. The Hele-Shaw apparatus models potential flow problems. Both the electrical analog and the Hele-Shaw apparatus extend the range of problems which may be investigated in the fluid mechanics laboratory.

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